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EMPIRICAL OBSERVATIONS ON THE SENSITIVITY OF HOT CATHODE IONIZATION TYPE VACUUM GAGES

by Robert L. Summers

Lewis Research Center
Cleveland, Ohio

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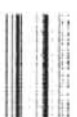

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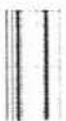
ABSTRACT

A study of empirical methods of predicting the relative sensitivities of hot cathode ionization gages is presented. Using previously published gage sensitivities, several rules for predicting relative sensitivity are tested. The relative sensitivity to different gases is shown to be invariant with gage type, in the linear range of gage operation. The total ionization cross section, molecular and molar polarizability, and refractive index are demonstrated to be useful parameters for predicting relative gage sensitivity. Using data from the literature, the probable error of predictions of relative gage sensitivity based on these molecular properties is found to be about 10 percent. A comprehensive table of predicted relative sensitivities, based on empirical methods, is presented.



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SUMMARY

A study of empirical methods of predicting the relative sensitivities of hot cathode ionization gages is presented. Using previously published gage sensitivities, several rules for predicting relative sensitivity are tested.

The relative sensitivity to different gases is shown to be invariant with gage type, in the linear range of gage operation. The total ionization cross section, molecular and molar polarizability, and refractive index are demonstrated to be useful parameters for predicting relative gage sensitivity.

Using data from the literature, the probable error of predictions of relative gage sensitivity based on these molecular properties is found to be about 10 percent.

A comprehensive table of predicted relative sensitivities, based on empirical methods, is presented.

INTRODUCTION

The hot cathode ionization gage (hereinafter called ion gage) is the most widely used device for measuring pressures of less than 1×10^{-3} torr. A given ion gage will be usable over five to seven decades of pressure. But, in various forms, ion gages can span the pressure range from 1×10^{-1} to 1×10^{-13} torr.

In operation, the ion gage creates ions by electron bombardment of the gas whose pressure is to be measured. The ratio of the ion current to the electron current is then divided by a specific quantity, the gage sensitivity, to give the gas pressure.

The gage sensitivity is a function of several variables, each of which must be known or controlled. The gage configuration and electrical parameters must be known. The gage must be properly mounted in (or on) the vacuum system, and finally, the nature of the gas within the system must either be known or assumed.

For each combination of these variables, there exists a gage sensitivity which may be mathematically combined with the gage currents to yield pressure. Unfortunately, the gage sensitivity is known for only a few combinations of the above variables, and it cannot be calculated with adequate accuracy. On the other hand, individual calibration of gages for each gas is difficult and time consuming.

An alternative approach is an empirical estimate of gage sensitivity, based on the gage's performance in other gases, the performance of other gages in the gas of interest, or on some property of the gas. This report examines a number of such empirical methods of estimating gage sensitivity. By considering the published values of gage sensitivity for a variety of cases, the reliability of these methods is estimated.

SYMBOLS

a_o	radius of first Bohr orbit of atomic hydrogen
G(e)	a nondimensional function of electron energy
i_+	ion current
i_-	electron current
$K_{1,2}$	gage constant, defined in eq. (2)
k	Boltzmann constant, 1.38×10^{-23} joules/K
M	molecular weight
m, m'	slope
N	Avogadro number, 6.02×10^{23} $(mol)^{-1}$
n	number of items in a set or sample
P	molar polarizability
p	pressure
$R_{1,2}$	relative sensitivity, defined in eq. (2)
r	refractive index
S	gage sensitivity, dimensions of $(pressure)^{-1}$
T	absolute temperature
V_c	gage collector potential, referenced to ground
V_f	gage filament potential, referenced to ground
V_g	gage grid potential, referenced to ground

V_i ionization potential

x, y variables

x_j, y_j one of a set of values of x and y, respectively

z number of molecular electrons

α molecular polarizability

ϵ dielectric constant

μ molecular electric dipole moment

ρ density

σ total ionization cross section, multiple of πa_o^2

$\overline{\sigma}$ peak total ionization cross section (PTICS), multiple of πa_o^2

$\sigma(E)$ total ionization cross section as function of electron energy

Subscripts:

1, 2 specific but undefined gases

Superscripts:

* most probable value, based on technique described in CORRELATION OF DATA section

ION GAGES AND GAGE SENSITIVITY

The defining equation for the ion gage is

$$p = \left(\frac{1}{S}\right)\left(\frac{i_+}{i_-}\right) \tag{1}$$

where p is the pressure, and S is the gage sensitivity in units of reciprocal pressure. The ion and electron currents are i_+ and i_-, respectively. In this relation, p is the pressure at the gage.

Improper mounting of the gage can cause the pressure at the gage to differ from that of the system. However, this problem falls outside the scope of this report. Several comprehensive sources are available (refs. 1 to 3), which detail proper gage usage to minimize or eliminate this problem. Throughout this report, it is assumed that the pressure at the gage adequately represents the system pressure.

Over a wide range of pressures, the sensitivity is independent of pressure. How-

ever, at very low pressures, residual currents create an apparent pressure dependence. Also, at high pressures, unacceptable sensitivity variations, called gage saturation, occur. The useful pressure range of the gage is taken to be that portion over which these nonlinearities are small.

For a specific gage and a specific gas environment, the sensitivity also depends on the electrical parameters. The electrical parameters are defined as the voltages applied to the various elements of the gage, and the currents flowing between the elements.

The magnitude of the currents influences the sensitivity only slightly. The main effect is a reduction of the useful range of the gage with increasing electron current. Increasing the electron current will cause gage saturation to occur at lower pressure.

The sensitivity, of course, varies with the gas. For a given gage, the gas identity and the applied voltages are the primary variables effecting the sensitivity.

The primary interest of this report is the gage sensitivity S, and the manner in which S varies with the gas environment within the gage. The scope of this report is restricted to those conditions under which the gage, the gas, and the voltages applied to the gage are the only significant variables affecting the gage sensitivity.

Gage Classification

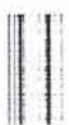
Ion gages are available in a wide variety of configurations or geometries. They may be classified into types, according to a design principle. The type is characterized either by the design or the inventor's name. Examples of this would be triode, inverted triode or Bayard-Alpert, and Scultz-Phelps.

A gage type may be further divided into subgroups called models. Usually, several models of a given type exist. They are characterized by a number, or a manufacturer's name and number. Examples of this are RG-75, 553, and WL-5966.

In this report, the words type and model are used in the senses just defined.

Gage Sensitivity

The sensitivity to nitrogen for various gage types will vary from 0.5 to 20 $torr^{-1}$, due to variations in gage geometry and applied voltages. The variation of sensitivity for a given gas among various gage models of the same type will be of the order of 50 percent. For apparently identical gages of the same model, the variation will be about 20 percent because of slight variations in geometry. Some gages have multiple filaments; here, due to small differences in position, the variation of sensitivity with different filaments may be 10 percent.



The sensitivity of a single gage to various gases will vary by a factor of 10, both larger and smaller, from the gage's nitrogen sensitivity. The primary mechanism which accounts for this variation is, of course, the ionization cross section of the gas in question. Attempts have been made (refs. 4 to 6) to calculate gage sensitivity and to account for sensitivity variations with gage type and gas species. These attemps have shown only limited success. The calculations of gage sensitivity are accurate enough to indicate that the basic mechanisms involved are understood. However, the accuracy is not sufficient for practical applications. Achievement of an accuracy higher than 80 percent requires gage calibration.

Estimating Gage Sensitivity

Dushman (ref. 1) suggests that the ratio of sensitivities for two gases is approximately independent of gage type. This rule is widely used, although the accuracy has never been well defined. In application of the Dushman rule, two terms are in general usage, and appear in the literature. They are the relative sensitivity and the gage constant. They are defined as

$$R_{1,2} = \frac{1}{K_{1,2}} = \frac{S_1}{S_2} \tag{2}$$

where $R_{1,2}$ is the relative sensitivity to gas 1, using gas 2 as a reference. In a similar fashion, $K_{1,2}$ is the gage constant. Using these terms, the Dushman rule can be stated as follows: The relative sensitivity and the gage constant are invariant with gage configuration.

This report reviews the published literature on gage sensitivity, in order to establish the accuracy of the Dushman rule.

Other references (refs. 1, and 6 to 8) also suggest relations between various properties of the gas molecule and the gage sensitivity for that gas. The properties used are the ionization cross section, the ionization potential, and the number of molecular electrons.

All these relations are considered in this report, and the error associated with their usage is established. In addition, a relation between gage sensitivity and molecular polarizability is postulated and tested. The primary molecular properties considered in this report are ionization cross section and molecular polarizability, as obtained directly or indirectly from the literature.

SOURCES OF GAGE SENSITIVITY DATA

For this report, the sources of data on gage sensitivity were manufacturers' literature and scientific journals and texts (refs. 7 to 25). Manufacturers' data must be approached with caution, since the original source is usually not specified. The various literature references, on the other hand, must be evaluated in light of the technique of calibration used and the exactness of specification of the operating parameters.

As an example of the importance of technique of calibration, references 10, 11, and 26 point out serious errors in the reference-standard McLeod gage. The importance of electrical parameters is demonstrated by references 7, 12, and 13, these authors have observed wide variations of gage sensitivity with changes in these parameters.

The data used in this report for ion gage sensitivity are summarized in table I (manufacturers' data) and table II (literature data). The data in the original references are presented in a variety of forms. Some of the references state the gage sensitivity, while other sources give the gage constant or the relative sensitivity.

These references represent only a portion of the available literature. Many others were considered, but are not included since they closely duplicate or parallel those selected. From the many publications in this field, those discussed in appendix A were selected to contribute to the correlations presented herein. Care was taken that this selection was a representative one, encompassing nearly all gases, nearly all gage geometries and associated electrical parameters, and most of the conventional calibration techniques.

DUSHMAN RULE

The ratio-of-sensitivities rule of reference 1 is in wide usage. The truth of this rule and its accuracy may be tested using the data of table II. The statement of the rule is

$$\left.\frac{S_1}{S_2}\right|_{\text{gage A}} = \left.\frac{S_1}{S_2}\right|_{\text{gage B}} \tag{3}$$

where gage A and gage B refer to two different sets of gage sensitivity data in table II. A form of equation (3) which facilitates intercomparison of data from many experimenters is one in which S_2 is always chosen as the sensitivity for a particular gas (e.g., nitrogen).

The test applied is a linear correlation of each set of data in table II with the average of all sets in table II. The details of the correlation are given below in the section CORRELATION OF DATA. These average senstivities are also listed in table II.

In this test, table I is excluded, not to impugn its worth, but because the source of the commercial data is not known. A correlation under such circumstances would be of little value, since it is not known which of the data given represent independent determinations, rather than transcriptions of other reported data (e.g., note the identity of data for manufacturers 3, 4, and 5 in table I).

CORRELATION OF GAGE SENSITIVITY WITH A MOLECULAR PROPERTY

The previous efforts to relate gage sensitivity to some molecular property of the gas in question are normally found to be contained in a minor statement in the body of a report on gage calibration. However, these statements do indicate that empirical estimates of gage sensitivity are an attractive alternate to the difficult task of individual gage calibration.

Reference 1 demonstrates an approximately linear relation between gage sensitivity and the number of molecular electrons. Reference 6, in turn, formalized this relation into the form of an equation.

Figure 1 explores this relation using the average-gage sensitivity data from table II. The equation of reference 6 is also shown. For the more conventional gases, the linear relation appears to hold reasonably well, although helium (He) and neon (Ne) show very large percentage deviations from the straight line. Furthermore, the sensitivity data for the less common gases do not fit the relation. Reference 8 suggests a relation, for the inert gases, between the logarithm of sensitivity and the first ionization potential. This relation is shown in figure 2, using the data of reference 10. The probable error (PE) of this relation is 6 percent. References 7 and 9 have correlated gage sensitivity with the total ionization cross section at a particular electron energy, as suggested by reference 1. Reference 27 does the reverse, and uses gage sensitivity to estimate the ionization cross section.

Previous efforts to predict gage sensitivity by various means have accepted the Dushman rule discussed in the previous section. These predictions of the ratio of gage sensitivities for two gases were made by observing a similar ratio of some other physical property of the molecule. Usually, the gage configuration played no part in the prediction.

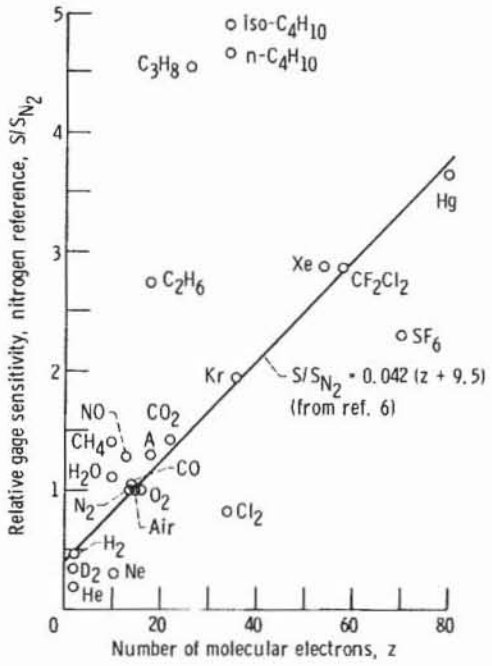


Figure 1. - Ionization gage sensitivity as function of number of molecular electrons. Sensitivity data taken from table II; average gage data used when possible.

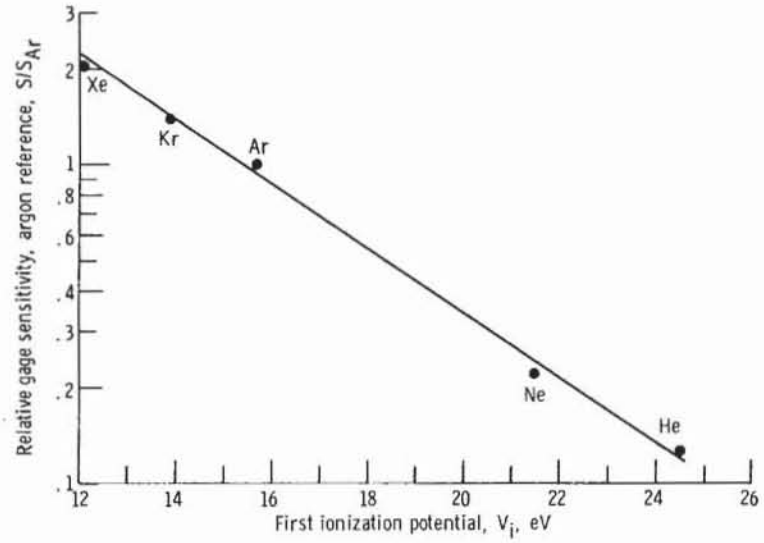


Figure 2. - Ionization gage sensitivity for noble gases as function of first ionization potential. (Sensitivity data from ref. 10.)

PEAK TOTAL IONIZATION CROSS SECTION

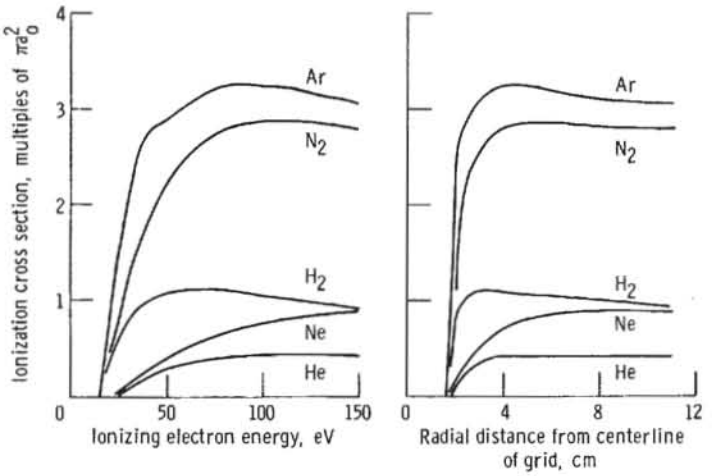
The possibility of a relation between peak total ionization cross section (PTICS) and gage sensitivity arose upon consideration of the method of calculating gage sensitivity. In such calculations, the process of integration of the ionization cross section over the gage volume tends to diminish the effect of the variation of ionization cross section with electron energy and places emphasis on the maximum value of ionization cross section.

This process is shown in figure 3. In figure 3(a), the ionization cross section is presented as a function of electron energy. However, the calculation of gage sensitivity (detailed in refs. 4 and 5) requires a spatial relation between ionization cross section and gage geometry. To obtain this relation, the ionizing electron energy is equated to the field potential in the gage, which, in turn, can be related to gage geometry. By this process, figure 3(a) may be converted into figure 3(b). In essence, the area under each curve in figure 3(b) is proportional to gage sensitivity. The dominance of the peak value of ionization cross section is apparent in figure 3(b).

The correlation of PTICS with gage sensitivity is attempted in the form

$$\frac{S_1}{S_2} = \frac{\bar{\sigma}_1}{\bar{\sigma}_2} \tag{4}$$

where $\bar{\sigma}$ is the PTICS.



(a) As function of ionizing electron energy. (Data from ref. 29.)

(b) As function of gage geometry. Gage type, RG-75; 150 volts; gage collector potential, -30 volts; gage filament potential, 0 volt. (Data transformed from fig. 3(a).)

Figure 3. - Ionization cross section.

To test this relation, an examination of published literature on ionization cross section has been made to compile data on PTICS.

Peak Total Ionization Cross Section Data

Direct data. - Reference 28 reviews the bulk of the published data on ionization cross section and performs a critical evaluation of these data. On the basis of the analysis in reference 28, reference 29 has been chosen by the author as the preferred source for values of PTICS used in the present report. It must be emphasized that the value of PTICS may be uncertain by as much as 10 to 20 percent for some of the gases.

Indirect data. - One of the following techniques may be used to estimate the PTICS for a given gas, where there is no value reported in the literature.

Summation of components: For gas mixtures, such as air, the PTICS of the components can be weighted in proportion to their number density and then summed to yield the PTICS of the mixture. This technique, of course, assumes no interaction between the component gases.

Correlation with total ionization cross section at a specific electron energy: The total ionization cross section reported at a specific electron energy may be correlated with reported PTICS data for the same gases, and then this correlation may be assumed to hold for related gases.

References 27 and 30 report the cross section for 75-electron-volt electrons for several gases and vapors. The PTICS data of reference 29 agree with the corresponding data of reference 30 to about 6 percent PE. The hydrocarbon data of reference 27 correlate with the corresponding data of reference 30 to about 6 percent PE. Sufficient data common to both references 27 and 29 were not available for a meaningful correlation.

Other methods: Reference 27 also presents a technique of calculating ionization cross section from the weighted sum of the mean square radii of the orbits of the atomic electrons. Reference 27 also suggests that the cross section of a molecule may be estimated by summing the cross sections of the individual atoms. These proposed methods are discussed in detail in references 30 and 31 and are shown to contain some serious errors. These techniques are, of course, available to estimate PTICS. However, sensitivities computed from the PTICS so derived have been in error by as much as a factor of 2.

Appendix B indicates the methods and sources used to obtain PTICS for all the gases considered herein. Table III lists these values of PTICS.

Molecular Polarizability

Reference 30 reports a proportionality between the ionization cross section for 75-electron-volt electrons and molecular polarizability. In addition, reference 30 presents a theoretical justification for such a relation. The possibility of a similar proportionality between PTICS $\bar{\sigma}$ and molecular polarizability α in the form

$$\frac{\bar{\sigma}_1}{\bar{\sigma}_2} = \frac{\alpha_1}{\alpha_2} \tag{5}$$

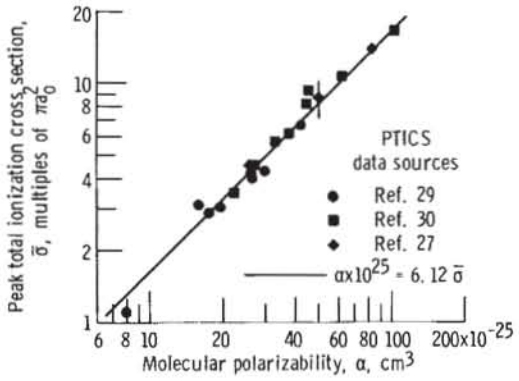


Figure 4. - Molecular polarizability as function of peak total ionization cross section. (All polarizability data taken from ref. 32.)

is tested in figure 4 using the data of references 27, 29, 30, and 32. Combining equations (4) and (5) yields equation (6)

$$\frac{S_1}{S_2} = \frac{\alpha_1}{\alpha_2} \tag{6}$$

A correlation is attempted using equation (6). When molecular polarizability values were not available, these values were deduced by one of the following means.

Molar polarizability. - The molar polarizability P is related to the molecular polarizability by

$$P = \frac{4\pi}{3} N\alpha = 2.54 \times 10^{24} \alpha \tag{7}$$

Reference 33 presents measurements of molar polarizability in binary solutions at infinite dilution.

Refractive index. - By the use of the Lorentz-Lorenz relation (ref. 33)

$$\frac{r^2 - 1}{r^2 + 2}\left(\frac{M}{\rho}\right) = \frac{4\pi}{3} N\alpha \tag{8}$$

the molecular polarizability may be derived from the refractive index r For gases at 1 atmosphere pressure and 0° C, equation (8) may be reduced, by an approximation, to

$$\alpha = 5.88 \times 10^{-21}(r - 1)\ cm^3 \tag{9}$$

Dielectric constant. - For nonpolar molecules, the molecular polarizability may be derived from the dielectric constant by use of the Clausius-Mosotti relation (ref. 33).

$$\frac{\epsilon - 1}{\epsilon + 2}\left(\frac{M}{\rho}\right) = \frac{4\pi}{3} N\alpha \tag{10}$$

Many of the gases of interest are polar, so that the electric moment must be considered. The Debye equation (ref. 33)

$$\frac{\epsilon - 1}{\epsilon + 2}\left(\frac{M}{\rho}\right) - \frac{4\pi}{9} N \frac{\mu^2}{kT} = \frac{4\pi}{3} N\alpha \tag{11}$$

can be used to derive the molecular polarizability for the gas of interest. The value of molecular polarizability can then be used in equation (6) to derive the gage sensitivity.

Molecular polarizabilities derived from equation (11) have been found to be reasonably accurate only in the case of slightly polar or nonpolar molecules. For molecules with large electric moments, equation (11) represents a small difference between two large quantities of similar size and may yield large errors.

All the data for polarizability used to test equation (6) are summarized in table IV.

CORRELATION OF DATA

The validities of the various empirical relations presented in this report (eqs. (3), (4), and (6)) were tested using data obtained from the literature. These data are summarized in tables II to IV.

To intercompare data from observers who used different units of S, the values of sensitivity for each gage were expressed in nondimensional form by dividing S by that gage's sensitivity for a reference gas. Equations (4) and (6) were thereby converted to

$$\frac{S}{S^*_{N_2}} = \frac{\bar{\sigma}}{\bar{\sigma}_{N_2}} \tag{4a}$$

$$\frac{S}{S^*_{N_2}} = \frac{\alpha}{\alpha_{N_2}} \tag{6a}$$

respectively, where the asterisk denotes the most probable value of sensitivity for the subscript gas.

To test the Dushman rule, equation (3) was converted to

$$\frac{S}{S^*_{Ar}} = \left(\frac{S}{S^*_{Ar}}\right)_{av} \tag{3a}$$

where the right-hand expression is the relative sensitivity of a fictitious "average gage," which will be defined below.

Correlation With Peak Total Ionization Cross Section

To test equation (4a), the value of $S^*_{N_2}$ for a given gage was determined as follows:

(1) A linear relation between S and $\bar{\sigma}/\bar{\sigma}_{N_2}$ was assumed, of the form

$$S = m\left(\frac{\bar{\sigma}}{\bar{\sigma}_{N_2}}\right)_{(29)} \tag{12}$$

where the number in parenthesis denotes the reference used, and the PTICS data of reference 29 are taken as correct.

(2) Using all of the available data for that gage, for all gases used with the gage that are also listed in reference 29, the most probable value of m was computed, on the assumptions that $\left(\bar{\sigma}/\bar{\sigma}_{N_2}\right)_{(29)}$ was without error and that all values of S had an equal probable percentage error.

(3) This computation led to a most probable value of sensitivity for N_2 as

$$S^*_{N_2} \equiv m \tag{13a}$$

(since $\bar{\sigma}/\bar{\sigma}_{N_2}$ is 1 for N_2), where

$$m = \frac{\sum_{j=1}^{n} \left(\frac{x_j}{S_j}\right)}{\sum_{j=1}^{n} \left(\frac{x_j}{S_j}\right)^2} \tag{13b}$$

$$x = \left(\frac{\bar{\sigma}}{\bar{\sigma}_{N_2}}\right)_{(29)} \tag{13c}$$

and j refers to the various gases, whose total number is n. This procedure had the following desirable features:

(a) When there was no experimental data for N_2, it was nevertheless possible to deduce $S^*_{N_2}$.

(b) When original data did include data for N_2, no extra weight was given to that data.

(4) The probable percentage error of S in equation (12) was computed as

$$\frac{\delta S}{S} = \frac{85}{\sqrt{n(n-1)}} \sum_{j=1}^{n} \left| \frac{mx_j - S_j}{S_j} \right| \tag{14}$$

Any data whose deviation from $m\left(\bar{\sigma}/\bar{\sigma}_{N_2}\right)_{(29)}$ exceeded $3(\delta S/S)$ were rejected, and steps (2) and (3) were then repeated. This criterion for rejection of data is similar to one often used in statistical analysis.

Values of $S/S^*_{N_2}$ thus obtained are listed in tables V and VI.

Correlation With Molecular Polarizability

To test equation (6a), the same procedure was used as in the correlation with $\bar{\sigma}$, except that the data of reference 32 were used for the values of relative molecular polarizability. Thus, the quantity $\left(\alpha/\alpha_{N_2}\right)_{(32)}$ replaces the quantity $\left(\bar{\sigma}/\bar{\sigma}_{N_2}\right)_{(29)}$ in equations (12) and (13c).

Values of $S/S^*_{N_2}$ thus obtained did not differ significantly from those listed in tables V and VI. Therefore, these values are not listed separately.

Test of Dushman Rule

To test equation (3a), the data of reference 23 were first used as convenient abscissas for a relation of the form of equation (12). Reference 23 lists values of S/S_{Ar} for a large number of gases (but not for N_2) and their accuracy (apparent only in retrospect) does justify the choice. However, the data of reference 23 were not used in such manner as to carry appreciably greater weight than the data of other references; it was necessary only that the data be reasonably accurate and consistent. The following steps were used for each gage:

(1) A linear relation between S and $\left(S/S_{Ar}\right)_{(23)}$ was assumed, of the form

$$S = m' \cdot \left(\frac{S}{S_{Ar}}\right)_{(23)} \tag{15}$$

(2) The most probable value of m' was computed from the data of table II, on the assumptions that $\left(S/S_{Ar}\right)_{(23)}$ was without error and that all values of S had equal probable percentage error. The computation is the same as equation (13b), with $x_j \equiv \left(S/S_{Ar}\right)_{(23)}$.

(3) Anomalous data were rejected from the computation of m', in the same manner as in step (4) of the correlation with $\bar{\sigma}$.

(4) Each of the values of sensitivity was converted to a nondimensional sensitivity S/S^*_{Ar} by dividing the published value of S by m'.

(5) The values of S/S^*_{Ar} for all gages, for a particular gas, were averaged to yield a value $S/S^*_{Ar\ av}$ for that gas, as representing a fictitious "average gage."

(6) The probable percentage error for any one gage was taken as

$$\frac{\delta\left(\frac{S}{S^*_{Ar}}\right)}{\frac{S}{S^*_{Ar}}} = \frac{85}{\sqrt{n(n-1)}} \sum_{j=1}^{n} \left| \frac{\left(\frac{S}{S^*_{Ar}}\right)_j - \left(\frac{S}{S^*_{Ar}}\right)_{av}}{\left(\frac{S}{S^*_{Ar}}\right)_{av}} \right| \tag{16}$$

where the summation is taken over all gases. It is of incidental interest that the average of all values of $\delta(S/S_{Ar})/(S/S_{Ar})$ thus obtained is not significantly different from the average of all values of a similar quantity obtained by summing over all gages for any one gas.

To maintain consistency of presentation throughout this report, the values of relative sensitivity $\left(S/S^*_{Ar}\right)_{av}$ obtained in step (5) were divided by $\left(S_{N_2}/S^*_{Ar}\right)_{av}$ to yield the values of $\left(S/S^*_{N_2}\right)_{av}$ listed in the last column of table II. The result of equation (16) is unchanged if the reference gas is nitrogen rather than argon.

RESULTS

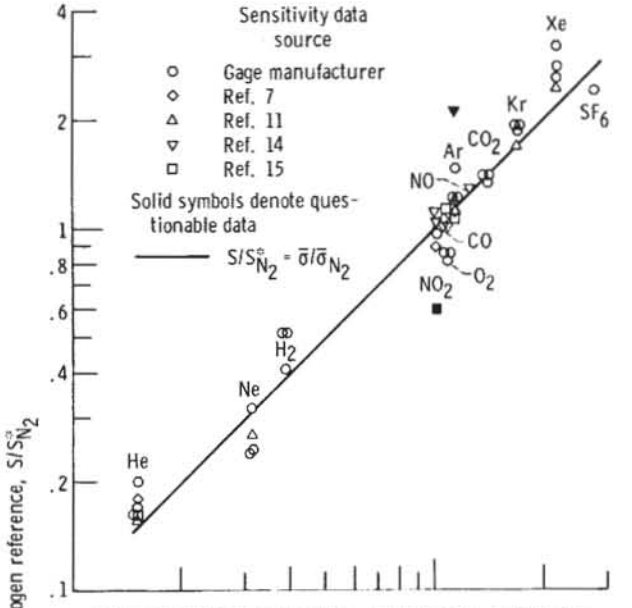
Dushman Rule

Using the 110 data for the first 14 gases of table II, the test of the Dushman rule yielded a probable error (PE) of 7.5 percent for all data. The deletion of four points (argon of ref. 14, nitrogen of ref. 15, and krypton and xenon of ref. 20) reduced the PE to 6.4 percent.

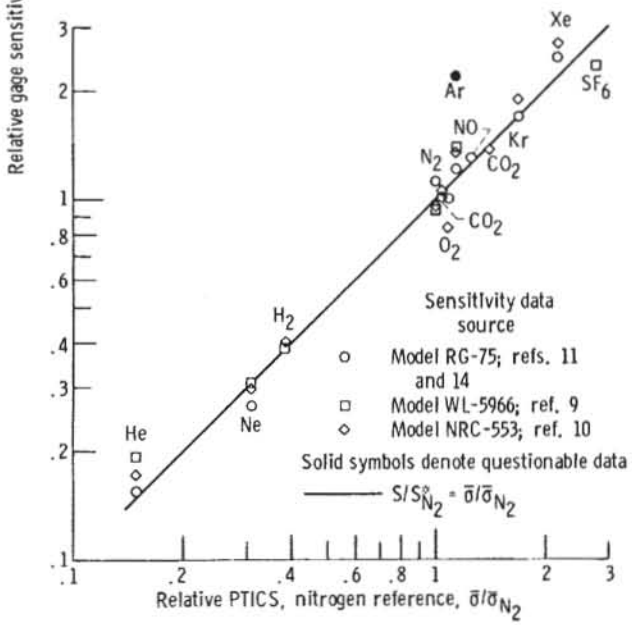
Ignoring the points deleted, the correlation for a single gage model (RG-75) showed a PE = 4.2 percent. Similarly, for a single gage type, PE = 4.5 and 7.7 percent for Bayard-Alpert and triode types, respectively.

Peak Total Ionization Cross Section - Sensitivity Correlation

Using the data of tables II and III, the gage sensitivity data were found to correlate with the PTICS data with a PE of 11.1 percent. The same four points, deleted in the Dushman rule correlation were deleted here. The correlation of gage sensitivity with PTICS has been divided into four overlapping categories. These categories are shown in figures 5(a) to (d) and discussed below. For these figures, the relative sensitivities of tables V and VI are used. The PTICS data are also converted to relative values by

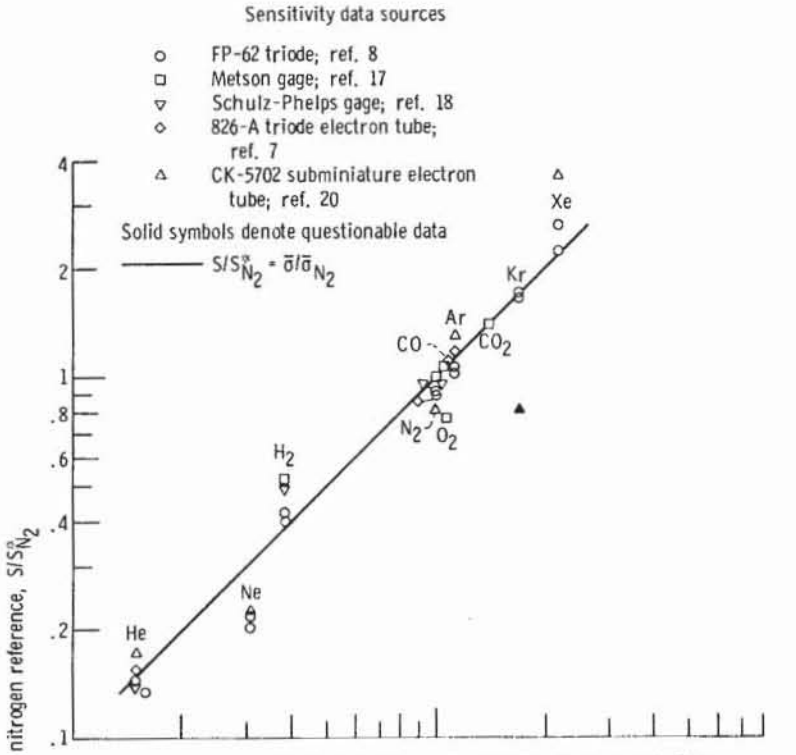


(a) For Bayard-Alpert type gage; model RG-75. (PTICS data from ref. 29.)

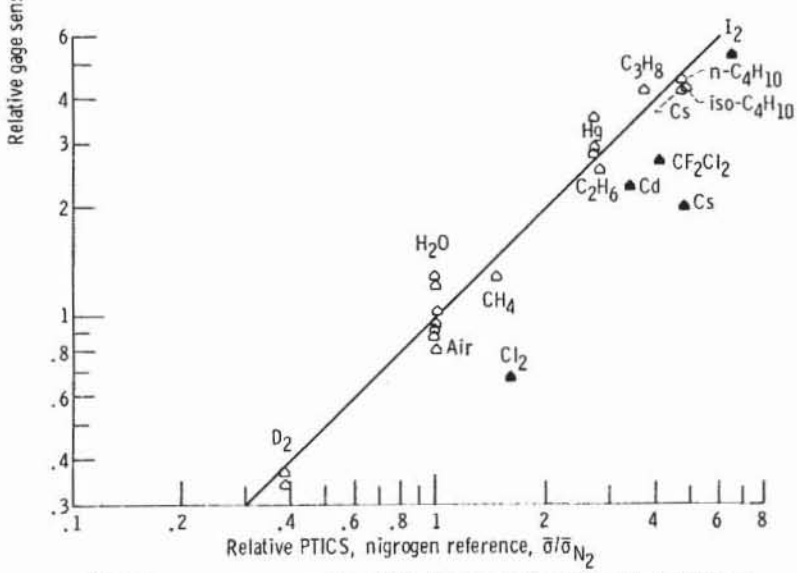


(b) For three models of Bayard-Alpert type gages. (PTICS data from ref. 29.)

Figure 5. - Relative ionization gage sensitivity as function of peak total ionization cross section (PTICS).



(c) For various types of ionization gages. (PTICS data from ref. 29.)



(d) For less common gases. (Sensitivity data from tables V and VI; PTICS data from table IV.)

Figure 5. - Concluded.

dividing all the PTICS data by the PTICS for nitrogen. If the correlation were perfect, the relative gage sensitivity would be numerically equal to the relative PTICS.

Correlation for several gages of same model. - Figure 5(a) presents data reported by several workers, as well as the manufacturer's data. The PE of all the data is 12 percent. By excluding the two points indicated in figure 5(a), the PE of the remainder becomes 10 percent. Excluding the manufacturer's data further decreases the PE to 6 percent.

Correlation for several models of same gage type. - Figure 5(b) shows the correlation for three models of Bayard-Alpert gages. The three gages differed mainly in their mechanical geometry; electrical parameters were quite similar. The PE of all the data is 10 percent. Excluding the questioned argon value, whose deviation is 50 percent, reduces the PE of the remainder to 8 percent.

Correlation for several gage types. - Figure 5(c) shows the correlation for a variety of gage types. The PE is 20 percent. Exclusion of data for xenon (Xe) and krypton (Kr) from reference 20 leads to a PE of 10 percent.

Correlation for less common gases. - Figure 5(d) shows a correlation for some less commonly encountered gases. The PTICS values for most of these gases were not available from reference 29; they were obtained as indicated in appendix B. Excluding the four questionable points in figure 5(d), the PE is 10 percent. Some of the gases, such as methane, mercury, and water, that are included in figure 5(d) are not particularly uncommon in vacuum environments. They are included herein since, due to their condensible nature, the data for these gases are probably less accurate than the data shown in figures 5(a) to (c). The air data are included here, since the PTICS was derived by the summation-of-components technique.

Several assumptions were made in converting the cesium gage sensitivity data of reference 25 to the form used herein. Because of these assumptions (see appendix A), these cesium data are listed as questionable. For the other questionable points, the PTICS data were derived by various means (see appendix B) and are perhaps less reliable.

Correlation of Sensitivity With Molecular Polarizability

Figure 6 shows the correlation between molecular polarizability and gage sensitivity for several gases, regardless of gage type. For figure 6, the relative sensitivities are from tables V and VI. The relative molecular polarizability data are from table IV. The PE of equation (6), for all data, is 12.4 percent.

As in the case of the Dushman rule and PTICS-sensitivity correlations, no significant difference in the degree of correlation as a function of gage type was noted.

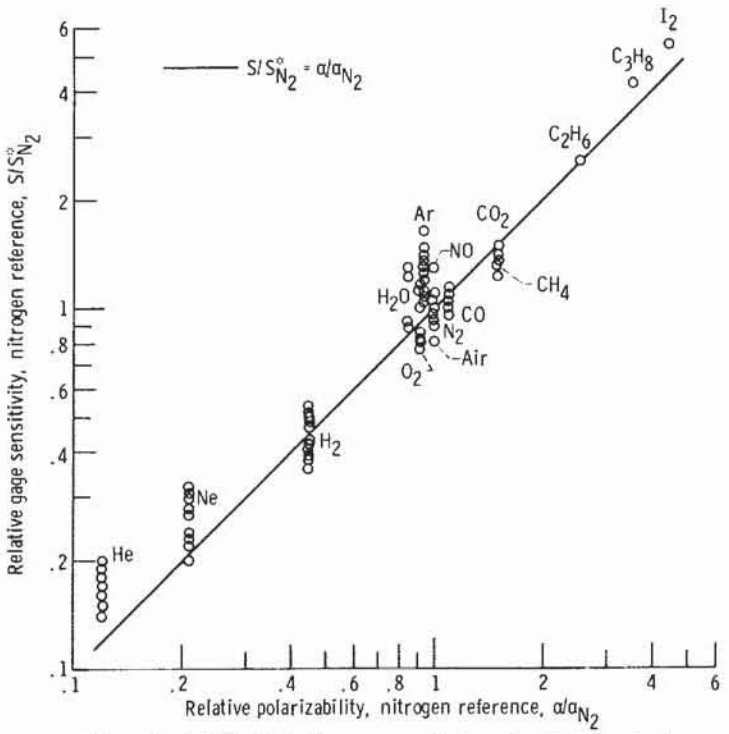


Figure 6. - Relative ionization gage sensitivity as function of molecular polarizability for various gases and various gage types. (Sensitivity data from tables V and VI; molecular polarizability data from table IV.

DISCUSSION

Based on the above correlations, the Dushman rule is shown to have a PE of 7 percent. The errors in the measured sensitivity data may account for a good portion of this error.

Figures 5(a) to (c) indicate that the correlations with PTICS for several gages of the same model, or same type, or different types are of the same order. The PE of equation (4) is about 11 percent. The PTICS data of reference 29, used in testing the PTICS-sensitivity correlation, can be assumed to have a PE of 5 to 10 percent. Also, the gage sensitivity data have a PE of the same order. It then follows that a PE of 11 percent for equation (4) is about as good as one could expect to achieve.

Factors Affecting Correlation

The degree of correlation obtained appears reasonable when the factors that may affect the correlation are examined individually.

Electrical parameter variations. - The variation of gage sensitivity with grid poten-

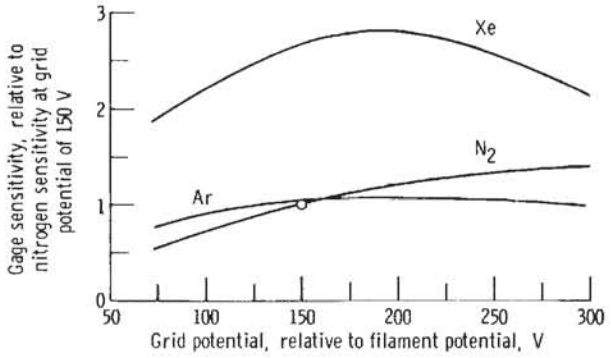


Figure 7. - Relative sensitivity of RG-75 ionization gage as function of grid potential.

tial is shown for one model of Bayard-Alpert gage in figure 7. Since, among all the references examined, grid potentials ranged from 100 to 250 volts, variations may be expected in the reported values of sensitivity. For example, in figure 7, the value of S_{Ar}/S_{N_2} ranges from 1.3 at V_g = 100 volts to 0.78 at V_g = 250 volts.

The relations shown in figure 7 are unique to the gage-gas combinations indicated. Any other gage-gas combination will exhibit a different variation of sensitivity with grid voltage. So few data of this type are available for the many gases and gage types considered in this report, that no attempt was made to incorporate this factor into the correlations.

Mechanical parameter variations. - Reference 6 shows that large sensitivity variations may result from small changes in gage geometry. Small changes in grid pitch or in filament-to-grid spacing may produce appreciable changes (as much as 20 percent) in sensitivity.

Reference 28 reports sensitivity differences of 10 percent between filaments in a multifilament gage. Sensitivity variations of the same order have been noted for a given gage over its useful lifetime. This is probably due to mechanical changes caused by normal usage.

Calibration technique. - Calibration errors of considerable size may occur if the reference-standard instrument itself generates or contains errors. Errors can also occur if the vacuum system used does not have a speed considerably greater than the speeds of gage pumping or local outgassing. Those data which have been discarded in the critical reviews of appendix A represent conditions in which the errors were so extreme as to be readily apparent. However, sources of error that are so mild as to produce errors of 10 or 20 percent are not always identifiable. Examination of each of the references reported in appendix A indicates that, on the average, the internal inconsistency of data in any one reference is of the order of 5 to 10 percent.

Peak total ionization cross section uncertainty. - An analysis of the data presented in reference 28 indicates that the PE of PTICS data of reference 29 is about 7 percent.

Comparison With Other Cross-Section Correlations

The data of reference 29 for total ionization cross section for each gas can be expressed in the form

$$\sigma(E) = \overline{\sigma}G(E) \tag{17}$$

To determine the extent to which G(E) is a single-valued function of electron energy, independent of gas type, the function G(E) was derived by averaging all of the tabulated data of reference 29 at each tabulated value of electron energy. The PE for G(E) was less than 6 percent over an electron energy range of 60 to 300 electron volts for all of the gases treated in reference 29.

Equation (17) infers a remarkable uniformity of the total-cross-section data. Because of this uniformity, a correlation of gage sensitivity with PTICS should yield about the same accuracy as a correlation using total ionization cross section at a particular electron energy.

To illustrate this point, a correlation of gage sensitivity (data of ref. 10) with ionization cross section at 145 electron volts (energy corresponding to the gage's grid potential) yielded a PE of 11 percent. A similar correlation using PTICS showed a PE of 9 percent. In both cases, the cross-section data were from reference 29.

While the PTICS estimate of gage sensitivity does not differ significantly from estimates based on ionization cross section at a specific electron energy, the PTICS method does offer the advantage of requiring no special knowledge of the gage configuration or parameters.

Predictions of Gage Sensitivity

In the preparation of this report, several sources were used to obtain the data required for the correlations performed. Out of the mass of data accumulated, only a part could be used.

Cross-section or polarizability data on over a hundred gases and vapors were accumulated. But gage sensitivities for only 25 of these were available. These 25 gases and vapors were used to test the accuracy of the relations between sensitivity, PTICS, and polarizability. The remaining data were arranged and are presented in table VII, along with the data for the 25 test gases, as predictions of gage sensitivity.

CONCLUDING REMARKS

The relative sensitivity of an ion gage has been shown to be invariant with gage type (Dushman's rule) with a probable error of 7 percent or less.

Also, the relative sensitivity is predicted to a probable error of 10 to 15 percent, directly from the peak total ionization cross section, the polarizability (molecular or molar), or the refractive index.

Generally, where molecular polarizability or PTICS was derived from other molecular parameters, the probable error was increased appreciably.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 19, 1969,
124-09-19-06-22.

APPENDIX A

REFERENCED DATA FOR IONIZATION GAGE SENSITIVITY

This appendix gives details of material covered by the various references that were used to establish the correlations presented herein.

Reference 7. - Two commercial triode electronic tubes (type 826-A) and a RG-75 Bayard-Alpert gage were calibrated using a McLeod gage. Pressures were above 1×10^{-5} torr. The reported nitrogen sensitivity seems very low. The authors note this and discuss possible bistable gage operation. The triode tubes were operated with the plates as the ion collector.

Electrical parameters: $i_- = 0.1$ milliampere
$V_c = 0$ volt
$V_g = 150$ volts
$V_f = 22.5$ volts

Reference 8. - Two FP-62 triode gages and a triode VG-1 gage were used. Pressure and method of calibration are not indicated in the reference. The neon sensitivities seem to be anomalous (as discussed in the CORRELATION OF DATA section).

Electrical parameters: $i_- = 0.5$ to 5.0 milliamperes
$V_f = 0$ volt
$V_g = 125$ volts
$V_c = -22$ volts

Reference 9. - Three Bayard-Alpert gages (type WL-5966) were calibrated over a pressure range of 1×10^{-5} to 0.1 torr, using a McLeod gage. The author gives a good discussion of the problems of operating gages at or near the high pressure limit of the gage. The sensitivities noted were from the linear region.

Electrical parameters: $i_- = 0.1$ milliampere
$V_c = 0$ volt
$V_g = 170$ volts
$V_f = 30$ volts

Reference 10. - The authors used a McLeod gage and a capacitance manometer to calibrate a NRC-553 Bayard-Alpert gage. Pressure was varied from 1×10^{-4} to 3×10^{-3} torr. Errors due to McLeod pumping were observed and reported. Problems due to contamination were reported in the use of ion gages in a methane environment.

Electrical parameters: $i_- = 0.1$ milliampere
$V_f = 25$ volts
$V_g = 170$ volts
$V_c = 0$ volt

Reference 11. - Measurements were made on a RG-75 Bayard-Alpert gage, using a Knudsen gage and a McLeod gage as reference standards. Known pressures were generated using a volume expansion technique. The McLeod gage was refrigerated to eliminate the pumping error.

Electrical parameters: $i_- = 0.1$ milliampere
$V_c = 0$ volt
$V_g = 180$ volts
$V_f = 30$ volts

Reference 13. - This work is an extension of an earlier investigation, that of reference 12. The gage used is a custom-designed Bayard-Alpert type similar to the RG-75. Two sensitivity modes were noted for the gage depending on the electrical parameters. Also, the sensitivity variation with grid voltage is reported.

Electrical parameters: $V_c = -20$ volts
$V_g = 260$ volts
$V_f = 0$ volt
$i_- = 1.0$ milliampere

Reference 14. - The gage calibrated was a RG-75, using the same parameters as reference 11. The technique used a mixture of two gases flowing into a system which has a mass spectrometer calibrated for one of the gases. Knowing the original mixture and the partial pressure of the known gas in the system, the partial pressure of the second gas is determined by the gas dynamics. The ion current output of the ionization gage is assumed to be an additive function of the individual ion currents.

The quoted argon sensitivity seems quite high, although the author does not offer an explanation. This datum was omitted in all the correlations.

Reference 15. - Calibration was performed in the range of 1×10^{-6} to 2×10^{-5} torr. The gage calibrated was a RG-75, using the electrical parameters of reference 11. Calibration was performed using a Knudsen gage. The author notes the low nitrogen sensitivity and states that a second similar gage showed a higher nitrogen sensitivity, but does not state the value. This datum was omitted in all the correlations.

Reference 16. - A type 507 triode gage was calibrated using a McLeod gage. Particular attention is given to gage pumping of oxygen and gaseous oxides. A 30 percent reduction in pressure indication is shown at the end of a 0.37 liter per second tubulation. The author suggests that the quoted helium sensitivity is high but offers no reason for such behavior.

Electrical parameters: $i_- = 5.0$ milliamperes
$V_g = 145$ volts
$V_c = -22$ volts
$V_f = 0$ volt

Reference 17. - Three gages were calibrated against a Knudsen gage. No electrical parameters are given. The gages are described only as a "commercial triode gage" and "Metson suppressor gages." Two Metson gages were used. However, only limited data are given for the second gage. Since this limited data closely paralleled that of the first Metson gage, only the data for the first Metson was used herein.

The oxygen data seem quite low, while the hydrogen data seem high; no comment is made by the authors.

Reference 18. - The design of a "high pressure" ionization gage is described by the authors. The gage was calibrated against a "Bayard-Alpert" gage and an oil manometer. This article gives an excellent discussion of the high pressure limitations of ionization gages.

Electrical parameters: $i_- = 0.05$ milliampere
$V_c = -60$ volts
$V_g = 60$ volts
$V_f = 0$ volt

Reference 19. - Using the gage and parameters of reference 23, the author calibrated a high pressure gage for water vapor. Known water vapor pressure was established by using ice at a known temperature and calculating the vapor pressure in a closed system over the ice.

Reference 20. - This reference describes the use of a CK-5702 subminiature beam power pentode as a vacuum gage. The data in table II were taken from figure 6 of the reference and, therefore, are subject to perhaps a 10 percent error in reading the figure. The xenon and krypton data seem to be anomalous and were rejected in all the correlations.

Reference 21. - The author gives data on WL-5966 Bayard-Alpert gages. Absolute sensitivities of gages are reported to vary by 20 percent between samples and by 10 percent between filaments within the same gage.

Electrical parameters: $i_- = 0.5$ milliampere
$V_f = 25$ volt
$V_c = 0$ volt
$V_g = 170$ volt

Reference 22. - A calibration of an unknown gage is presented for helium and deuterium, based on standard leaks and a flow system. Measurements are considered to be not much better than 20 percent.

Reference 23. - This reference gives relative gage sensitivities for a Leybold IM-1 gage. Calibration was performed by the volume expansion method.

Electrical parameters: $i_- = 1.0$ milliampere
$V_f = 0$ volt
$V_g = 180$ volts
$V_c = -40$ volts

Reference 24. - Measurements were made on a WL-5966 Bayard-Alpert gage to determine gage sensitivity to cesium vapor. A vapor pressure technique similar to that of reference 19 was used. The value in table VI was derived by assuming a gage sensitivity to nitrogen of 12 $torr^{-1}$ and a thermal transpiration correction from 200° to 50° C. The quoted cesium sensitivity of 52 $torr^{-1}$ is given in relative form in table VI as 4.33 times the nitrogen sensitivity.

Reference 25. - A measurement in saturated cesium vapor similar to that in reference 24 is described. Few details of the gage are given. The author quotes a gage constant for cesium of 0.055 as compared to 0.100 for air. This gives a cesium sensitivity of 1.82 times that of air. Assuming an air sensitivity of 1.00 relative to nitrogen, the cesium sensitivity becomes 1.82 times that of nitrogen.

APPENDIX B

PEAK TOTAL IONIZATION GAGE CROSS-SECTION DATA SOURCES

The sources of PTICS data for the 37 gases and vapors considered in the various correlations in this report are listed below.

Literature References

Reference 29. - Reference 29 was chosen as the preferred source of ionization cross-section data, based on the review work of reference 28. These data consist of cross-section measurements presented in tabular form. From these tables, the maximum value of cross section for each gas has been taken as the PTICS for that gas. These PTICS values are listed below. For each gas, the PTICS was divided by the PTICS for nitrogen to give a relative cross section. These data have a probable error of no more than 10 percent.

Gas or vapor	PTICS, $\bar{\sigma}$, multiples of πa_o^2	Relative PTICS, $\bar{\sigma}/\bar{\sigma}_{N_2}$	Gas or vapor	PTICS, $\bar{\sigma}$, multiples of πa_o^2	Relative PTICS, $\bar{\sigma}/\bar{\sigma}_{N_2}$
He	0.425	0.148	O_2	3.096	1.077
Ne	.890	.310	CO	3.018	1.050
A	3.25	1.13	CO_2	4.040	1.406
Kr	4.84	1.68	NO	3.580	1.246
Xe	6.21	2.16	N_2O	4.29	1.49
H_2	1.104	.384	CH_4	4.205	1.463
D_2	1.115	.388	C_2H_4	6.625	2.305
N_2	2.874	1.000	SF_6	7.92	2.76

Cross section	H_2O	Gas									
		H_2S	HCl	NH_3	C_2H_2	C_2H_6	C_3H_8	C_6H_6	CH_3Cl	C_4H_{10}	
										Normal	Iso
Cross section for 75-eV electrons, multiples of πa_o^2	2.85	6.18	4.54	3.42	5.69	8.05	10.7	16.3	9.08	13.5	13.9
Relative PTICS	.99	2.15	1.58	1.19	1.98	2.80	3.72	5.66	3.16	4.71	4.83

Reference 30. - Reference 30 reports cross-section measurements for 75-electron-volt electrons for 35 substances. The measurements consisted of the total current output of a mass spectrometer ionizer.

The 75-electron-volt cross sections were fitted to the PTICS data of reference 29 in the same manner as used in the correlation of sensitivity data with $\overline{\sigma}$. The deviation of reference 30 from reference 29 showed a PE of about 10 percent.

Reference 27. - Reference 27 reports cross-section measurements for 42 substances. The data are summarized in table IV of the reference; the units of cross section are arbitrary.

Cross section	Gas		
	CS_2	CN_2	HCN
Arbitrary cross section for 75-eV electrons	13.7	10.2, 7.16	4.48
Relative PTICS	4.77	3.55, 2.49	1.56

Reference 30 questions the data of reference 27 for the inorganic substances; therefore, these data were rejected herein. Of the remaining 32 gases, sufficient data common to both reference 27 and reference 29 did not exist for intercomparison of the two references. For this reason, the data of reference 27 were smoothed by comparing them with the previously smoothed PTICS data of reference 30, in the same manner as used in the correlation of sensitivity data with $\overline{\sigma}$.

For 26 gases common to both references 27 and 30, the data showed a PE of deviation from perfect correlation of 6 percent.

Air. - Using the data from reference 29 for nitrogen and oxygen and assuming that air is 80 percent nitrogen and 20 percent oxygen, a PTICS for air of 2.91 (πa_o^2) was computed. This gives a value of 1.01, relative to N_2.

Cadmium. - The value of 9.71 (πa_o^2) for the cross section of cadmium at 50 electron volts (ref. 31) was used. This value was divided by the PTICS for nitrogen of reference 29 to yield a relative value of 3.4.

Cesium. - The cross section for cesium was taken from reference 34. The PTICS value of 13.8 (πa_o^2) is converted to a relative value of 4.80. This includes a correction factor suggested by reference 28.

Chlorine. - Reference 27 develops the relative ionization cross section of two gases by first summing the mean square radii of the orbits of the atomic electrons of each atom. Then, reference 27 postulates a rule that the cross section of each molecule is the summation of the cross sections of its individual atoms. Using these rules, the relative PTICS for molecular chlorine was estimated to be 1.6.

Dichlorodifluoromethane (CCl_2F_2). - Using reference 27, and the same reasoning as in the case of chlorine, the calculated relative PTICS was 4.1.

Iodine. - Using reference 27, and the same reasoning as in the case of chlorine, the calculated relative PTICS was 6.5.

Mercury. - Reference 28 shows the PTICS for mercury may range from 6 to 8 (πa_o^2). A relative value of 2.8 was used, although the value may be as low as 2.1.

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TABLE I. - IONIZATION GAGE SENSITIVITY, AS PRESENTED BY SEVERAL MANUFACTURERS

Gas	Manufacturer						
	1	2	3	4	5	6	7
	Gage type[a]						
	BAR	BAR	T	BAE	BAR	T	BARN
	Ionization gage sensitivity						
	Gage constant, N_2 reference	Gage constant, N_2 reference	Gage constant, air reference			Sensitivity for 5-mA emission, mA/torr	Emission for 0.1 mA per torr sensitivity, mA
He	4.80	6.2	5.6	5.6	5.6	14	6.7
Ne	3.0	4.2	3.8	3.8	3.8	---	----
Ar	.66	.84	.76	.76	.76	162	----
Kr	.52	.53	.48	.48	.48	---	----
Xe	.37	.37	.33	.33	.33	---	----
H_2	2.40	2.0	1.8	1.8	1.8	46	----
N_2	1.00	1.00	.9	.9	.9	110	0.95
O_2	1.20	1.18	1.1	1.1	1.1	85	----
CO	.93	.94	.85	.85	.85	112	----
CO_2	.73	.73	.66	.66	.66	120	----
Air	1.0	1.1	1.0	1.0	1.0	100	1.0
H_2O	1.1	1.12	1.0	1.0	1.0	---	----
Hg	.28	.29	.26	.26	.26	---	----
I_2	.18	----	----	----	----	---	----
Cd	.42	----	----	----	----	---	----
SF_6	.4	----	----	----	----	---	----

[a]Gage type abbreviations:

BAE Bayard-Alpert, with electron-bombardment outgas

BAR Bayard-Alpert, with resistance outgas

BARN Bayard-Alpert, with resistance outgas, and Nottingham shield

T triode, with resistance outgas

TABLE II. - IONIZATION GAGE SENSITIVITIES AS REPORTED IN THE LITERATURE

Gas	Reference																			Average gage, average of all references, S/S_{N_2}
	7		8			9	10	11	13	14	15	16	17		18	19	20	21	22	23	
	Gage model																				
	826-A[a]	RG-75	FP-62	FP-62	VG-1	WL-5966[b]	NRC-553	RG-75	Special B-A	RG-75	RG-75	507	Triode	Metson[c]	Special, high pressure	7676[d]	CK-5702[e]	WL-5966	Special B-A	IM-1	
	Ionization gage sensitivity																				
	$(torr)^{-1}$	$(torr)^{-1}$	$(torr)^{-1}$	$(torr)^{-1}$	$(torr)^{-1}$	$(torr)^{-1}$	S/S_{Ar}	S/S_{Ar}	S/S_{Ar}	S/S_{N_2}	S/S_{Ar}	$(torr)^{-1}$	$(torr)^{-1}$	$(torr)^{-1}$	$(torr)^{-1}$	S/S_{N_2}	S/S_{N_2}	$(torr)^{-1}$	$(torr)^{-1}$	S/S_{Ar}	
He	0.35	0.58	0.77	0.70	2.88	2.5	0.127	0.128	0.17	----	0.15	4.0	----	----	0.09	---	0.21	---	1.93	0.1283	0.18
Ne	----	----	1.08	1.08	4.65	4.0	.220	.221	.26	----	----	----	----	----	----	---	.41	---	----	.2407	.30
Ar	2.6	3.5	5.50	5.27	22.6	18.	1.000	1.000	1.0	1.89	1.00	22.4	----	----	----	---	1.6	---	----	1.000	1.29
Kr	----	----	8.9	8.4	32.9	----	1.39	1.40	1.53	----	----	----	----	----	----	---	1.0	---	----	1.333	1.94
Xe	----	----	12.0	13.0	50.9	----	2.02	2.02	2.22	----	----	----	----	----	----	---	4.4	30	----	2.190	2.87
H_2	----	----	2.14	2.10	8.65	5.0	.298	-----	----	----	----	8.0	12.5	0.36	.32	---	----	---	----	.2808	.46
N_2	2.0	2.8	4.90	4.40	18.2	12.0	.705	-----	----	1.00	0.56	21.0	23.5	.69	.6	---	1.0	11	----	------	1.00
O_2	2.5	3.5	-----	-----	-----	----	.616	-----	----	.90	----	24.0	20.	.53	----	---	----	---	----	------	1.01
CO	----	----	-----	-----	-----	----	.780	-----	----	.90	----	----	25.	.71	.62	---	----	12	----	.823	1.05
CO_2	----	----	-----	-----	-----	----	1.01	-----	----	----	----	----	32.	.96	----	---	----	---	----	1.163	1.42
Air	2.2	3.3	-----	-----	-----	----	-----	-----	----	----	----	17.0	----	----	----	---	----	---	----	.7127	1.00
H_2O	----	----	-----	-----	-----	----	-----	-----	----	----	----	----	21.	.84	----	1.4	----	---	----	------	1.12
Hg	----	----	15.0	14.5	72.0	----	-----	-----	----	----	----	----	----	----	----	---	----	---	----	------	3.64
D_2	----	----	-----	-----	-----	----	-----	-----	----	----	----	----	----	----	----	---	----	---	3.37	.2855	.35
CH_4	----	----	-----	-----	-----	----	-----	-----	----	----	----	----	----	----	----	---	----	---	----	1.015	----
C_2H_6	----	----	-----	-----	-----	----	-----	-----	----	----	----	----	----	----	----	---	----	---	----	1.992	----
C_3H_8	----	----	-----	-----	-----	----	-----	-----	----	----	----	----	----	----	----	---	----	---	----	3.282	----
n : C_4H_{10}	----	----	-----	-----	-----	----	-----	-----	----	----	----	----	----	----	----	---	----	---	----	3.543	----
iso : C_4H_{10}	----	----	-----	-----	-----	----	-----	-----	----	----	----	----	----	----	----	---	----	---	----	3.360	----
NO	----	----	-----	-----	-----	----	-----	-----	----	1.16	----	----	----	----	----	---	----	---	----	------	----
SF_6	----	----	-----	-----	-----	30	-----	-----	----	----	----	----	----	----	----	---	----	---	----	------	----
Cl_2	----	----	-----	-----	-----	----	-----	-----	----	----	.64	----	----	----	----	---	----	---	----	------	----
CF_2Cl_2	----	----	-----	-----	-----	----	-----	-----	----	----	----	----	----	----	----	---	----	---	----	2.1	----

[a]Average of two gages tested; commerical electronics triode.

[b]Average of three gages tested.

[c]First of two gages reported.

[d]Closely resembles type of ref. 18. Hereinafter, the two are combined as a single data set.

[e]Commercial electronics subminiature tetrode.

TABLE III. - VALUES OF PEAK TOTAL IONIZATION CROSS SECTION (PTICS)

USED IN CORRELATIONS

[Sources of all data are given in appendix B.]

Gas	PTICS, $\bar{\sigma}$, multiples of πa_o^2	Relative PTICS, $\bar{\sigma}/\bar{\sigma}_{N_2}$	Gas	PTICS, $\bar{\sigma}$, multiples of πa_o^2	Relative PTICS, $\bar{\sigma}/\bar{\sigma}_{N_2}$
Direct PTICS data			PTICS derived from ionization cross section at specific electron energy (75 eV, unless noted)		
He	0.425	0.148	H_2O	2.85	0.99
Ne	.890	.310	HCl	4.54	1.58
Ar	3.25	1.13	H_2S	6.18	2.15
Kr	4.84	1.68	NH_3	3.42	1.19
Xe	6.21	2.16	CS_2	13.7	4.77
H_2	1.104	.384	$(CN)_2$	7.2 to 10.0	2.5 to 3.5
D_2	1.115	.388	HCN	4.48	1.56
N_2	2.874	1.000	Cd[b]	9.7	3.4
O_2	3.08	1.072	C_2H_6	8.05	2.80
CO	3.018	1.050	C_3H_8	10.7	3.72
CO_2	4.040	1.406	n : C_4H_{10}	13.5	4.71
NO	3.580	1.246	iso : C_4H_{10}	13.9	5.88
N_2O	4.29	1.49	C_6H_6	16.3	5.66
CH_4	4.205	1.463	C_2H_2	5.69	1.98
C_2H_4	6.625	2.305	CH_3Cl	9.08	3.16
SF_6	7.92	2.76			
Cs	13.8	4.8	PTICS calculated according to methods of ref. 27		
Hg	7.7	2.8			
Air[a]	2.91	1.01	CF_2Cl_2	11.8	4.1
			I_2	18.7	6.5
			Cl_2	4.6	1.6

[a]Assumes that sum of PTICS of components equals total PTICS.

[b]Ionization cross section for 50-eV electrons.

TABLE IV. - VALUES OF MOLECULAR POLARIZABILITY USED

IN CORRELATIONS

Gas	Molecular polarizability (ref. 32), α, cm^3	Molar polarizability (ref. 33), P_o, cm^3	Refractive index (ref. 35), r - 1	Dielectric constant (ref. 35), ϵ - 1	Relative molecular polarizability, [a] α/α_{N_2}
He	[b] 2.1×10^{-25}	----	0.036×10^{-4}	----------	0.12
Ne	[b] 3.7	----	----------	0.127×10^{-4}	.21
Ar	[b] 16.5	----	.281	----------	.94
H_2	7.9	----	----------	----------	.45
N_2	17.6	----	----------	----------	1.00
O_2	16.0	----	----------	----------	.91
CO	19.5	----	----------	----------	1.11
CO_2	26.5	----	----------	----------	1.50
Air	[b] 17.2	----	.293	----------	.98
H_2O	[b] 14.6×10^{-25} to [b] 15.1×10^{-25}	----	0.25×10^{-4} to 0.26×10^{-4}	----------	0.83 to 0.86
NO	[b] 17.4×10^{-25}	----	0.297×10^{-4}	----------	0.99
N_2O	30.0	----	----------	----------	1.70
H_2S	37.8	----	----------	----------	2.15
HCl	26.3	----	----------	----------	1.49
HCN	25.9	----	----------	----------	1.47
CS_2	87.4	----	----------	----------	4.96
$(CN)_2$	50.1	----	----------	----------	2.85
NH_3	22.6	----	----------	----------	1.28
Cl_2	46.1	----	----------	----------	2.62
I_2	[b] 78.7	20.0	----------	----------	4.47
CH_4	26.0	----	----------	----------	1.48
C_2H_2	33.3	----	----------	----------	1.89
C_2H_4	42.6	----	----------	----------	2.42
C_2H_6	44.7	----	----------	----------	2.54
C_3H_8	62.9	----	----------	----------	3.57
C_6H_6	103.2	----	----------	----------	5.86
CH_3Cl	45.6	----	----------	----------	2.59

[a] Conversion from literature values to relative polarizability was performed using equations given in this report.

[b] Values of molecular polarizability were derived from molar polarizability, refractive index, or dielectric constant values listed.

TABLE V. - RELATIVE IONIZATION GAGE

SENSITIVITIES; MANUFACTURERS' DATA

Gas	Gage type[a]						
	BAR	BAR	T	BAE	BAR	T	BARN
	Relative gage sensitivity, $S/S^*_{N_2}$; derived from table I						
He	0.20	0.17	0.16	0.16	0.16	0.14	0.14
Ne	.32	.24	.24	.24	.24	----	----
Ar	1.47	1.21	1.22	1.22	1.22	1.64	----
Kr	1.86	1.92	1.93	1.93	1.93	----	----
Xe	2.6	2.8	3.2	3.2	3.2	----	----
H_2	.41	.51	.52	.52	.52	.47	----
N_2	.96	1.02	1.03	1.03	1.03	1.12	1.02
O_2	.81	.86	.84	.84	.84	.86	----
CO	1.04	1.08	1.09	1.09	1.09	1.14	----
CO_2	1.33	1.40	1.40	1.40	1.40	1.22	----
Air	.96	.93	.92	.92	.92	----	.97
H_2O	.88	.91	.92	.92	.92	----	----
Hg	3.5	3.5	3.6	3.6	3.6	----	----
I_2	5.4	----	----	----	----	----	----
Cd	2.3	----	----	----	----	----	----
SF_6	2.4	----	----	----	----	----	----

[a]Gage type abbreviations:

BAE Bayard-Alpert, with electron-bombardment outgas

BAR Bayard-Alpert, with resistance outgas

BARN Bayard-Alpert, with resistance outgas, and Nottingham shield

T triode, with resistance outgas

TABLE VI. - RELATIVE IONIZATION GAGE SENSITIVITIES; LITERATURE DATA

Gas	Reference																			
	7		8			9	10	11	13	14	15	16	17		18 and 19	20	21	22	23	24	25
	Gage model																				
	826-A[a]	RG-75	FP-62	FP-62	VG-1	WL-5966[b]	NRC-553	RG-75	Special B-A	RG-75	RG-75	507	Triode	Metson[c]	7676	CK-5702[d]	WL-5966	Special B-A	IM-1	WL-5966	Special B-A
	Relative ionization gage sensitivity, $S/S^*_{N_2}$; derived from table II																				
He	0.15	0.18	0.14	0.14	0.14	0.19	0.17	0.15	0.18	----	0.16	0.19	----	----	0.14	0.15	----	0.19	0.16	----	----
Ne	----	----	.20	.22	.23	.31	.30	.27	.28	----	----	----	----	----	----	.32	----	----	.31	----	----
Ar	1.18	1.11	1.03	1.07	1.12	1.38	1.34	1.20	1.06	2.11	1.06	1.07	----	----	----	1.30	----	----	1.28	----	----
Kr	----	----	1.66	1.70	1.63	----	1.87	1.68	1.63	----	----	----	----	----	----	.81	----	----	1.71	----	----
Xe	----	----	2.24	2.63	2.52	----	2.71	2.43	2.37	----	----	----	----	----	----	3.60	2.53	----	2.81	----	----
H_2	----	----	.40	.42	.43	.38	.40	----	----	----	----	.38	0.54	0.52	0.49	----	----	----	.36	----	----
N_2	.88	.89	----	----	----	----	.95	----	----	1.11	.60	1.00	1.01	1.00	.93	.81	.93	----	----	----	----
O_2	1.11	1.11	----	----	----	----	.83	----	----	1.00	----	1.15	.86	.77	----	----	----	----	----	----	----
CO	----	----	----	----	----	----	1.05	----	----	1.00	----	----	1.07	1.07	.96	----	1.01	----	1.06	----	----
CO_2	----	----	----	----	----	----	1.36	----	----	----	----	----	1.37	1.39	----	----	----	----	1.49	----	----
Air	.96	1.04	----	----	----	----	----	----	----	----	----	.81	----	----	----	----	----	----	.91	----	----
H_2O	----	----	----	----	----	----	----	----	----	----	----	----	.90	1.22	1.30	----	----	----	----	----	----
Hg	----	----	2.80	2.94	3.56	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----
D_2	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	.34	.37	----	----
CH_4	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	1.30	----	----
C_2H_6	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	2.56	----	----
C_3H_8	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	4.21	----	----
n : C_4H_{10}	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	4.55	----	----
iso : C_4H_{10}	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	4.31	----	----
NO	----	----	----	----	----	----	----	----	----	1.29	----	----	----	----	----	----	----	----	----	----	----
SF_6	----	----	----	----	----	2.31	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----
Cl_2	----	----	----	----	----	----	----	----	----	----	.68	----	----	----	----	----	----	----	----	----	----
CF_2Cl_2	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	2.70	----	----
Cs	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	4.33	2.02

[a]Average of two gages tested; commercial electronics triode.

[b]Average of three gages tested.

[c]First of two gages reported.

[d]Commercial electronics subminiature tetrode.

TABLE VII. - EMPIRICAL ESTIMATES OF IONIZATION GAGE SENSITIVITY

Substance	Formula	Relative ionization gage sensitivity, S/S_{N_2}	Source and type of data	
			Reference	Description
Acetaldehyde	C_2H_4O	2.6	27	Cross section (75 eV)
Acetone	$(CH_3)_2CO$	3.6	33	Polarizability
		4.0	27	Cross section (75 eV)
		3.6	35	Refractive index
Acetylene	C_2H_2	1.9	32	Polarizability
		2.0	30	Cross section (75 eV)
Air		1.0	Table II	Average gage
		.98	35	Refractive index
Ammonia	NH_3	1.3	32	Polarizability
		1.2	30	Cross section (75 eV)
		1.3	35	Refractive index
Amylene:				
iso-	iso-C_5H_{10}	5.9	30	Cross section (75 eV)
cyclo-	cy-C_5H_{10}	5.8	30	Cross section (75 eV)
Argon	Ar	1.3	Table II	Average gage
		1.1	29	PTICS
		1.2	30	Cross section (75 eV)
		.9	35	Refractive index
Benzene	C_6H_6	5.9	32	Polarizability
		5.8	33	Polarizability
		5.7	30	Cross section (75 eV)
		5.9	27	Cross section (75 eV)
		6.0	35	Refractive index
Benzoic acid	C_6H_5COOH	5.5	33	Polarizability
Bromine	Br	3.8	35	Refractive index
Bromomethane	CH_3Br	3.7	27	Cross section (75 eV)
Butane:				
n-	n-C_4H_{10}	4.9	23	Gage sensitivity
		4.7	30	Cross section (75 eV)
iso-	iso-C_4H_{10}	4.6	23	Gage sensitivity
		4.9	30	Cross section (75 eV)
Cadmium	Cd	2.3	Table V	Manufacturer's data
		3.4	31	Cross section (50 eV)
Carbon dioxide	CO_2	1.4	Table II	Average gage
		1.4	29	PTICS
		1.5	32	Polarizability
		1.5	35	Refractive index
		1.4	30	Cross section (75 eV)
Carbon disulfide	CS_2	5.0	32	Polarizability
		4.7	33	Polarizability
		4.8	27	Cross section (75 eV)
Carbon monoxide	CO	1.05	Table II	Average gage
		1.05	29	PTICS
		1.1	32	Polarizability

TABLE VII. - Continued. EMPIRICAL ESTIMATES OF IONIZATION GAGE SENSITIVITY

Substance	Formula	Relative ionization gage sensitivity, S/S_{N_2}	Source and type of data	
			Reference	Description
Carbon tetrachloride	CCl_4	6.0	32	Polarizability
		6.3	33	Polarizability
Cesium	Cs	4.3	24	Gage sensitivity
		2.0	25	Gage sensitivity
		4.8	34	PTICS
Chlorine	Cl_2	.68	15	Gage sensitivity
		2.6	33	Polarizability
		1.6	27	Calculated cross section
Chlorobenzene	C_6H_5Cl	7.0	33	Polarizability
Chloroethane	C_2H_5Cl	4.0	30	Cross section (75 eV)
Chloroform	$CHCl_3$	4.7	32	Polarizability
		4.8	33	Polarizability
		4.8	35	Refractive index
Chloromethane	CH_3Cl	2.6	32	Polarizability
		3.2	30	Cross section (75 eV)
		3.1	27	Cross section (75 eV)
Cyanogen	$(CN)_2$	2.8	32	Polarizability
		3.6	27	Cross section (75 eV)
		2.7	39	Refractive index
Cyclohexylene	C_6H_{12}	7.9	30	Cross section (75 eV)
		6.4	27	Cross section (75 eV)
Deuterium	D_2	.35	Table II	Average gage
		.38	29	PTICS
Dichlorodiflоromethane	CCl_2F_2	2.7	23	Gage sensitivity
		4.1	27	Calculated cross section
Dichloromethane	CH_2Cl_2	3.7	32	Polarizability
Dinitrobenzene:	$C_6H_4(NO_2)_2$			↓
o-		7.8	33	
m-		7.8	33	
p-		7.6	33	
Ethane	C_2H_6	2.6	23	Gage sensitivity
		2.8	30	Cross section (75 eV)
		2.5	32	Polarizability
Ethanol	C_2H_5OH	3.6	33	Polarizability
		2.9	39	Refractive index
Ethyl acetate	$CH_3COOC_2H_5$	5.0	33	Polarizability
Ethyl ether	$(C_2H_5)_2O$	5.1	33	Polarizability
		5.1	35	Refractive index
Ethylene	C_2H_4	2.3	29	PTICS
		2.4	32	Polarizability
		2.2	30	Cross section (75 eV)
		2.2 to 2.5	27	Cross section (75 eV)
Ethylene oxide	$(CH_2)_2O$	2.5	27	Cross section (75 eV)

TABLE VII. - Continued. EMPIRICAL ESTIMATES OF IONIZATION GAGE SENSITIVITY

Substance	Formula	Relative ionization gage sensitivity, S/S_{N_2}	Source and type of data	
			Reference	Description
Helium	He	0.18	Table II	Average gage
		.15	29	PTICS
		.13	30	Cross section (75 eV)
		.12	35	Refractive index
Heptane	C_7H_{16}	8.6	27	Cross section (75 eV)
Hexadiene:				
1,5-	$1,5\text{-}C_6H_{10}$	6.4	27	Cross section (75 eV)
cyclo-	$cy\text{-}C_6H_{10}$	6.0	27	Cross section (75 eV)
Hexane	C_6H_{14}	6.6	33	Polarizability
Hexene:				
1-	$1\text{-}C_6H_{12}$	5.9	27	Cross section (75 eV)
cyclo-	$cy\text{-}C_6H_{10}$	6.4	27	Cross section (75 eV)
Hydrogen	H_2	.46	Table II	Average gage
		.38	29	PTICS
		.41	30	Cross section (75 eV)
		.45	32	Polarizability
		.44	35	Refractive index
Hydrogen bromide	HBr	2.0	32	Polarizability
Hydrogen chloride	HCl	1.5	32	Polarizability
		1.6	30	Cross section (75 eV)
		2.0	27	Cross section (75 eV)
		1.5	35	Refractive index
Hydrogen cyanide	HCN	1.5	32	Polarizability
		1.6	27	Cross section (75 eV)
Hydrogen floride	HF	1.4	32	Polarizability
Hydrogen iodide	HI	3.1	32	Polarizability
Hydrogen sulfide	H_2S	2.2	32	Polarizability
		2.2	30	Cross section (75 eV)
		2.3	27	Cross section (75 eV)
		2.1	35	Refractive index
Iodine	I_2	5.4	Table V	Manufacturer's data
Iodomethane	CH_3I	4.2	27	Cross section (75 eV)
Isoamyl alcohol	$C_5H_{11}OH$	2.9	33	Polarizability
Isobutylene	C_4H_8	3.6	30	Cross section (75 eV)
Krypton	Kr	1.9	Table II	Average gage
		1.7	29	PTICS
		1.7	30	Cross section (75 eV)
Lithium	Li	1.9	34	PTICS
Mercury	Hg	3.6	Table II	Average gage
		2.8	28	PTICS

TABLE VII. - Continued. EMPIRICAL ESTIMATES OF IONIZATION GAGE SENSITIVITY

Substance	Formula	Relative ionization gage sensitivity, S/S_{N_2}	Source and type of data	
			Reference	Description
Methane	CH_4	1.4	23	Gage sensitivity
		1.5	29	PTICS
		1.6	30	Cross section (75 eV)
		1.4 to 1.8	27	Cross section (75 eV)
		1.5	32	Polarizability
		1.5	35	Refractive index
Methanol	CH_3OH	1.8	32	Polarizability
		1.9	35	Refractive index
Methyl acetate	CH_3COOCH_3	4.0	33	Polarizability
Methyl ether	$(CH_3)_2O$	3.0	27	Cross section (75 eV)
		3.0	35	Refractive index
Naphthalene	$C_{10}H_8$	9.7	33	Polarizability
Neon	Ne	.30	Table II	Average gage
		.31	29	PTICS
Nitrobenzene	$C_6H_5NO_2$	7.2	33	Polarizability
Nitrogen	N_2	1.0	Normalizing point for all data	
Nitrotoluene (o-, m-, p-)	$C_6H_4CH_3NO_2$	8.5	33	Polarizability
Nitric oxide	NO	1.3	14	Gage sensitivity
		1.2	29	PTICS
		1.0	35	Refractive index
Nitrous oxide	N_2O	1.5	29	PTICS
		1.7	32	Polarizability
		1.7	35	Refractive index
		1.3 to 2.1	27	Cross section (75 eV)
Oxygen	O_2	1.0	Table II	Average gage
		1.1	29	PTICS
		.9	32	Polarizability
		.9	35	Refractive index
Pentane:				
n-	$n\text{-}C_5H_{17}$	6.2	30	Cross section (75 eV)
		6.0	27	Cross section (75 eV)
		5.7	35	Refractive index
iso-	$iso\text{-}C_5H_{17}$	6.0	30	Cross section (75 eV)
neo-	$(CH_3)_4C$	5.7	30	Cross section (75 eV)
Phenol	C_6H_5OH	6.2	33	Polarizability
Phosphine	PH_3	2.6	27	Cross section (75 eV)
Potassium	K	3.6	34	PTICS

TABLE VII. - Concluded. EMPIRICAL ESTIMATES OF IONIZATION GAGE SENSITIVITY

Substance	Formula	Relative ionization gage sensitivity, S/S_{N_2}	Source and type of data	
			Reference	Description
Propane	C_3H_8	4.2	23	Gage sensitivity
		3.7	30	Cross section (75 eV)
		3.7 to 3.9	27	Cross section (75 eV)
		3.6	32	Polarizability
Propene oxide	C_3H_6O	3.9	27	Cross section (75 eV)
Propene:				
n-	n-C_3H_6	3.3	30	
		3.2 to 3.7	27	
cyclo-	cy-C_3H_6	3.6	30	
Rubidium	Rb	4.3	34	PTICS
Silver perchlorate	$AgClO_4$	3.6	33	Polarizability
Sodium	Na	3.0	34	PTICS
Stannic iodide	SnI_4	6.7	33	Polarizability
Sulfur dioxide	SO_2	2.1	32	Polarizability
		2.3	35	Refractive index
Sulfur hexafloride	SF_6	2.3	9	Gage sensitivity
		2.8	29	PTICS
Toluene	$C_6H_5CH_3$	6.8	33	Polarizability
Trinitrobenzene	$C_6H_3(NO_2)_3$	9.0	33	Polarizability
Water	H_2O	1.1	Table II	Average gage
		1.0	30	Cross section (75 eV)
		.8	35	Refractive index
Xenon	Xe	2.9	Table II	Average gage
		2.2	29	PTICS
		2.4	30	Cross section (75 eV)
Xylene:				
o-	o-$C_6H_4(CH_3)_2$	7.8	33	Polarizability
p-	p-$C_6H_4(CH_3)_2$	7.9	33	Polarizability

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